

STUDY OF DRIFT-FIELD SOLAR CELLS
DAMAGED BY LOW-ENERGY PROTONS

Contract NAS 5-9627

Report Covering Period of September 10 to October 15, 1965

J. De Pangher
R. A. Breuch
D. L. Crowther

APPROVED

A. Andrew
A. Andrew
Environmental Effects
Aerospace Sciences Laboratory

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CONTENTS

	<u>Page</u>
1. OBJECTIVE	1
2. WORK SUMMARY	1
3. CONFORMANCE OR NON-CONFORMANCE WITH THE WORK SCHEDULE	2
4. ANALYSIS OF WORK	2
5. RELIABILITY PROCEDURES	4
6. ADEQUACY OF FUNDS	5
7. CHANGES IN PERSONNEL	5
8. FUTURE WORK	6
 FIGURE CAPTIONS	 7
Figures 1-9	
 LIST OF TABLES	 8
Tables 1-3	

1. OBJECTIVE

The objective is to conduct an irradiation study of drift-field solar cells (supplied by NASA) with low energy protons. The experimental data on the irradiated cells are to consist of I-V curves and spectral response curves. The data are to be analyzed with the aid of a theoretical solar cell model.

2. WORK SUMMARY

An irradiation experiment was made with 30 drift-field solar cells and 12 uniform solar cells used as control cells. The modifications to the irradiation apparatus resulted in a very efficient conduct of the experiment and yielded a large quantity of I-V curve data and spectral response data. The irradiation included 10 drift-field cells which were received on September 27, the first day of the irradiation experiment which continued until October 1.

The cells were mounted on copper blocks which were attached to six brass disks. Leads were attached to the cells and then to a connector for each disk. The disks were irradiated in vacuum and then were removed for the taking of the I-V curves and the spectral response measurements. Table 1 serves to identify the cells, their positions on the disks, and the proton energies to which they were irradiated. Each I-V curve or set of spectral response data is identified by a code number which is made up from the disk number, the run number, and the cell-position number. For example, the code number, 16-6-4, refers to Disk 16, Run 6, and Cell-Position 4. An inspection of Table 1 shows this cell to be a RCA 10-ohm-cm cell irradiated with 1.04-Mev protons. Run numbers 0,1,2,3,4,5,6, and 7, are assigned the proton fluences as given in Table 2. The 10 drift-field cells received on September 27 were mounted on copper blocks having the designations, N75, N76,..., N84.

3. CONFORMANCE OR NON-CONFORMANCE TO SCHEDULE

All of the 30 drift-field solar cells received from NASA have been irradiated and a considerable quantity of data is on hand. The analysis is proceeding satisfactorily and, hence, the work is considered to be on schedule.

4. ANALYSIS OF THE WORK

A computer program has been worked out to fit the modified diode equation

$$I = I_{sc} \left[1 - e^{-\frac{q(V + R_s I - V_{oc})}{nkT}} \right] \quad (1)$$

to four points on an I-V curve: $(I_{sc}, 0)$, (I_1, V_1) , (I_2, V_2) , and $(0, V_{oc})$. The objective of the program is to compute n , R_s , and P_{max} and the coordinates of P_{max} . The points, (I_1, V_1) and (I_2, V_2) , are chosen to be on opposite sides of the maximum-power point. The fit to the I-V curves obtained for Disk 16 is satisfactory, and is therefore assumed to be good for the other disks.

Figure 1 shows the I-V curves obtained for the drift-field solar cell, TI 3-2, which was irradiated with 1.04-Mev protons on September 29. The I-V curve for Run 0 is coded 16-0-1 and is a pre-irradiation curve. The I-V curve for Run 7 is coded 16-7-1 and is a post-irradiation curve taken on October 1. The degradation of the I-V curves with increasing proton fluence is evident. After Eq. (1) was fitted to four points on each I-V curve, values of I and V were calculated in the computer program to give the points shown for the I-V curves coded 16-0-1 and 16-7-1. The good fit of the empirical data to the actual curves is evident. Figure 2 shows the spectral response curves for this drift-field cell for different proton fluences. The ordinate is the relative short-circuit current per incident photon. Experimental points are plotted only for the curve coded 16-0-1 to show the wavelengths which are transmitted by each one of the 14 filters.

Figures 3 and 4 show the I-V curves and spectral response curves for the drift-field cell, TI 4-2. This cell has a 12-micron drift-field region compared to the 25-micron drift-field region for the cell, TI 3-2.

Figures 5 and 6 show the I-V curves and spectral response curves for the uniform RCA N/P, 10-ohm-cm cell.

Table 3 summarizes the I-V curve data as analyzed by the computer program for all the operable cells on Disk 16 irradiated by 1.04-Mev protons. It includes the results for a Hoffman 10 ohm-cm N/P cell in addition to the cells already mentioned.

Figures 7-9 show the relative degradation of the short-circuit current (I_{sc}) of the open-circuit voltage (V_{oc}), and of the maximum power (P_m) for the cells TI 3-2, TI 4-2, and RCA 10-ohm-cm irradiated with 1.04-Mev protons as functions of the proton fluence. Included for each curve are the initial values of the parameter involved. The light source used for these measurements was an O.C L.I. sun simulator calibrated with a standard cell to give 140 mw/cm² at the measurement position.

From Earl Alexander of Texas Instruments (TI) it was determined that cell TI 3-2 has about a 25 microndrift-field region with about 3 orders of magnitude change in impurity atom density in the base layer while cell TI 4-2 has a 12 micron drift-field region with about 4 orders of magnitude change in impurity atom density. Since the range of a 1.04 MeV proton in silicon is about 18 microns and the drift field region contributes the greater part to the cell response then on a relative degradation basis TI 3-2 should degrade more than TI 4-2. In other words a 1.04-MeV proton damages only and nearly all of the drift field region in TI 3-2 while in TI 4-2 a good fraction of the damage is entirely outside the drift-field region. This is verified for all 3 degradation curves. However, on an absolute basis cell TI 3-2, since it has a larger drift-field region or collection volume and less

impurity atom variation, has a considerably higher initial I_{sc} and P_m but not V_{oc} since V_{oc} increases with decreasing drift field size and increasing impurity atom concentration. In fact, because of the higher initial values of P_m and I_{sc} , the I_{sc} and P_m for cell TI 3-2 stays above cell TI 4-2 out to the highest proton fluence of 1.53×10^{12} p/cm² despite its more rapid relative degradation. Cell TI 3-2 had a higher final P_m than RCA 10 and another Hoffman 10 ohm-cm uniform cell irradiated at the same time.

5. RELIABILITY PROCEDURES

The irradiation and fluence-measuring apparatus were modified to increase the probability for a successful irradiation experiment. All vacuum bellows were omitted within the equipment. One bellows had to be used to connect the apparatus to the vacuum system of the Van de Graaff accelerator. A 4-inch diameter oil diffusion pump connected directly to the 10-ft. drift tube yielded a pressure of 5×10^{-6} torr at the center of the drift tube in less than 10-min. The apparatus gave an easy accurate alignment optically and then with the proton beam. A quartz disk having a conducting ring served to simultaneously view the unscattered beam spot and beam current. This arrangement plus a TV camera and a beam-current meter allowed the Van de Graaff operator to rapidly adjust the proton beam at the four different energies which were employed. On the way to the insulated solar-cell disk the scattered protons pass through a defining aperture which was maintained at a negative bias to stop secondary electrons from penetrating it. Before the scattered beam was admitted to the solar-cell disk the scattered proton current density was measured with an insulated plate inserted between the aperture and the solar cell disk. The insulated plate contained four insulated quadrants. If the currents to the four quadrants were not quite equal, the end of the drift tube was moved slightly to equalize them. Initial checks showed that the current to the solar-cell disk was equal to the sum of the currents to the four quadrants.

Checks were made periodically on the I-V plotter with a disk containing four unirradiated solar cells. For only one disk, Disk 15, were there found small changes in the output of the O.C.L.I. solar simulator and the stability was improved by replacing the xenon bulb.

The filter-wheel spectrometer was automated to change the filters at the end of each data print-out on a digital recorder but was carefully watched for malfunctions during the data taking. The excellent consistency of the data in successive or repeated measurements served to check on the performance of the filter-wheel spectrometer. Background measurements were used to correct the ratios of the short-circuit currents from the irradiated cell to the reference cell were corrected. In this case two like voltage-to-frequency converters were employed on the 0.1 volt scales (0.1 volts gives 100,000 cycles/sec) to measure the short-circuit currents through 20-ohm resistors. The counts for the irradiated cell was measured each time for 5000 counts from the reference cell.

6. ADEQUACY OF FUNDS

The funds still remaining under the contract should be adequate for a careful data analysis on the solar cells which have already been irradiated but not enough to irradiate more cells and perform an additional analysis.

7. CHANGES IN PERSONNEL

Participating personnel have been:

J. De Pangher	Staff Scientist
D. L. Crowther	Research Scientist
E. A. Lodi	Senior Scientist
H. E. Pollard	Senior Thermodynamics Engineer
R. A. Breuch	Thermodynamics Engineer
G. D. Jones	Research Laboratory Analyst
G. N. Biren	Research Laboratory Analyst
	Van de Graaff operators

8. FUTURE WORK

The data analysis will continue with the reduction of the original data to a more useful form for presentation in the final report and for analysis with the theoretical solar cell model.

FIGURE CAPTIONS

- Figure 1 Current-voltage curves for the drift-field solar cell, TI 3-2
- Figure 2 Spectral response curves for the drift-field solar cell, TI 3-2
- Figure 3 Current voltage curves for the drift-field solar cell, TI 4-2
- Figure 4 Spectral response curves for the drift-field solar cell, TI 4-2
- Figure 5 Current-voltage curves for the uniform RCA 10-ohm-cm N/P solar cell
- Figure 6 Spectral-response curves for the uniform RCA 10-ohm-cm N/P solar cell
- Figure 7 Degradation of the relative short-circuit currents for three irradiated solar cells
- Figure 8 Degradation of the relative open-circuit voltages for three irradiated solar cells
- Figure 9 Degradation of the relative maximum powers for three irradiated solar cells

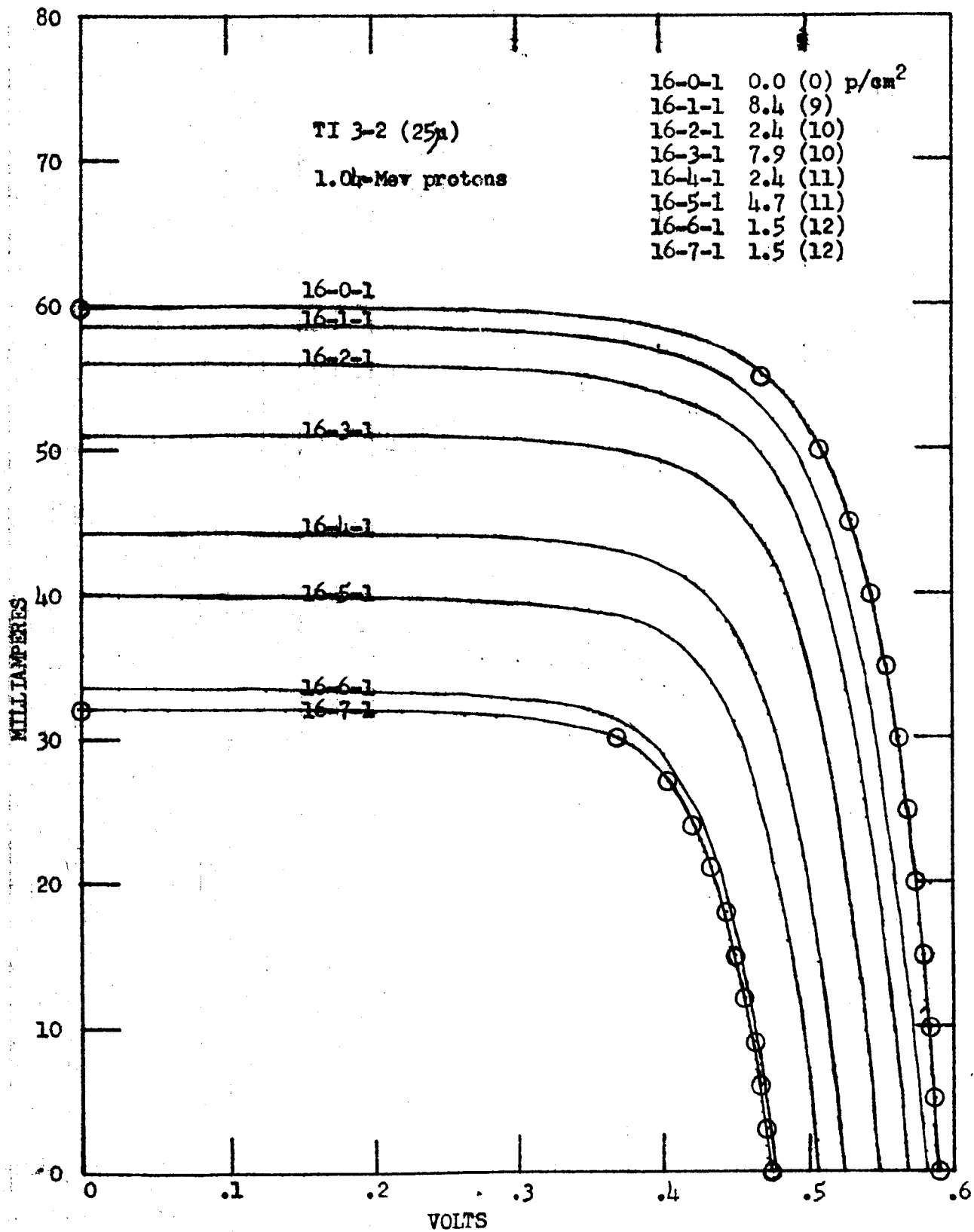


FIGURE 1

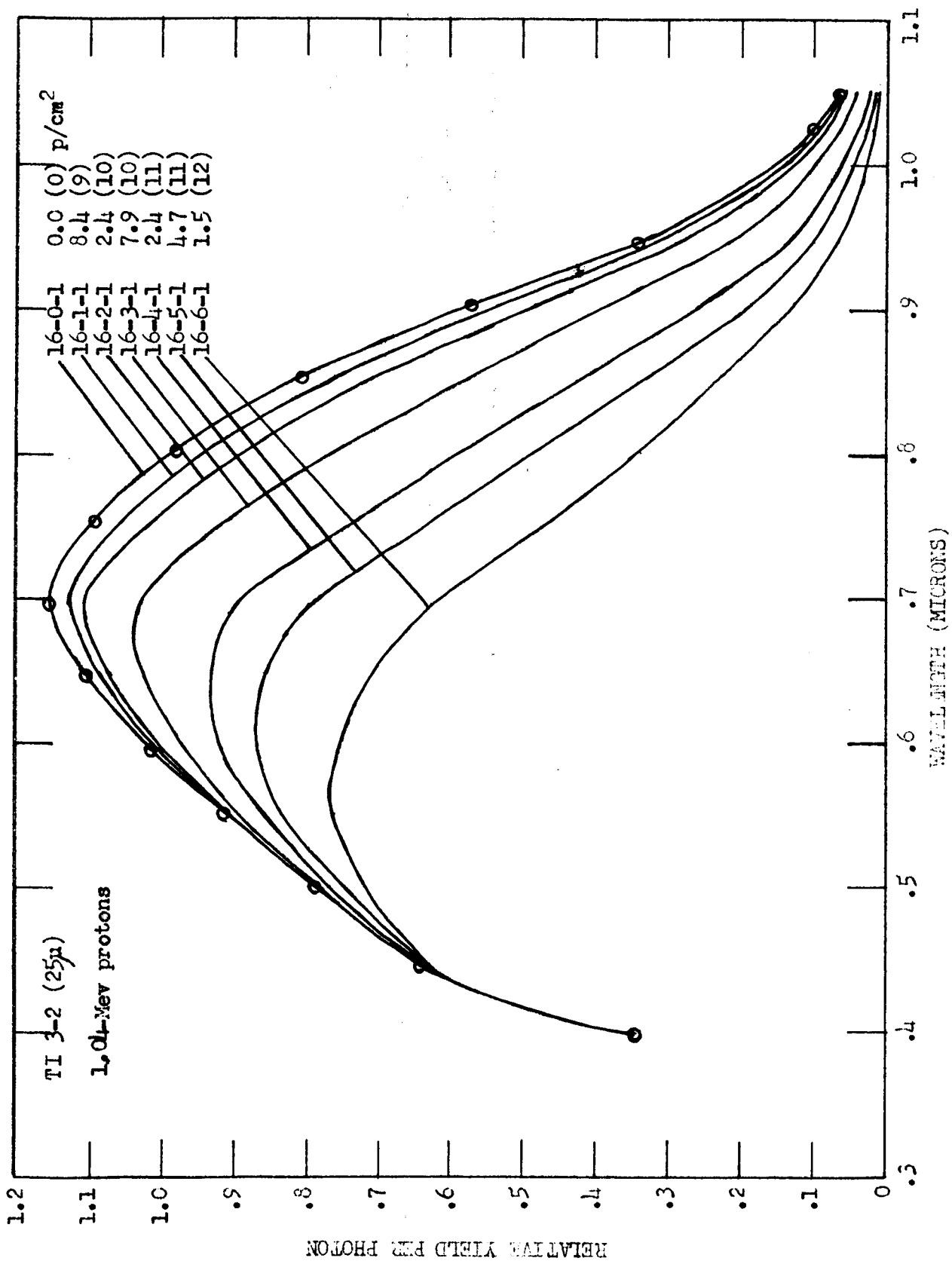


FIGURE 2

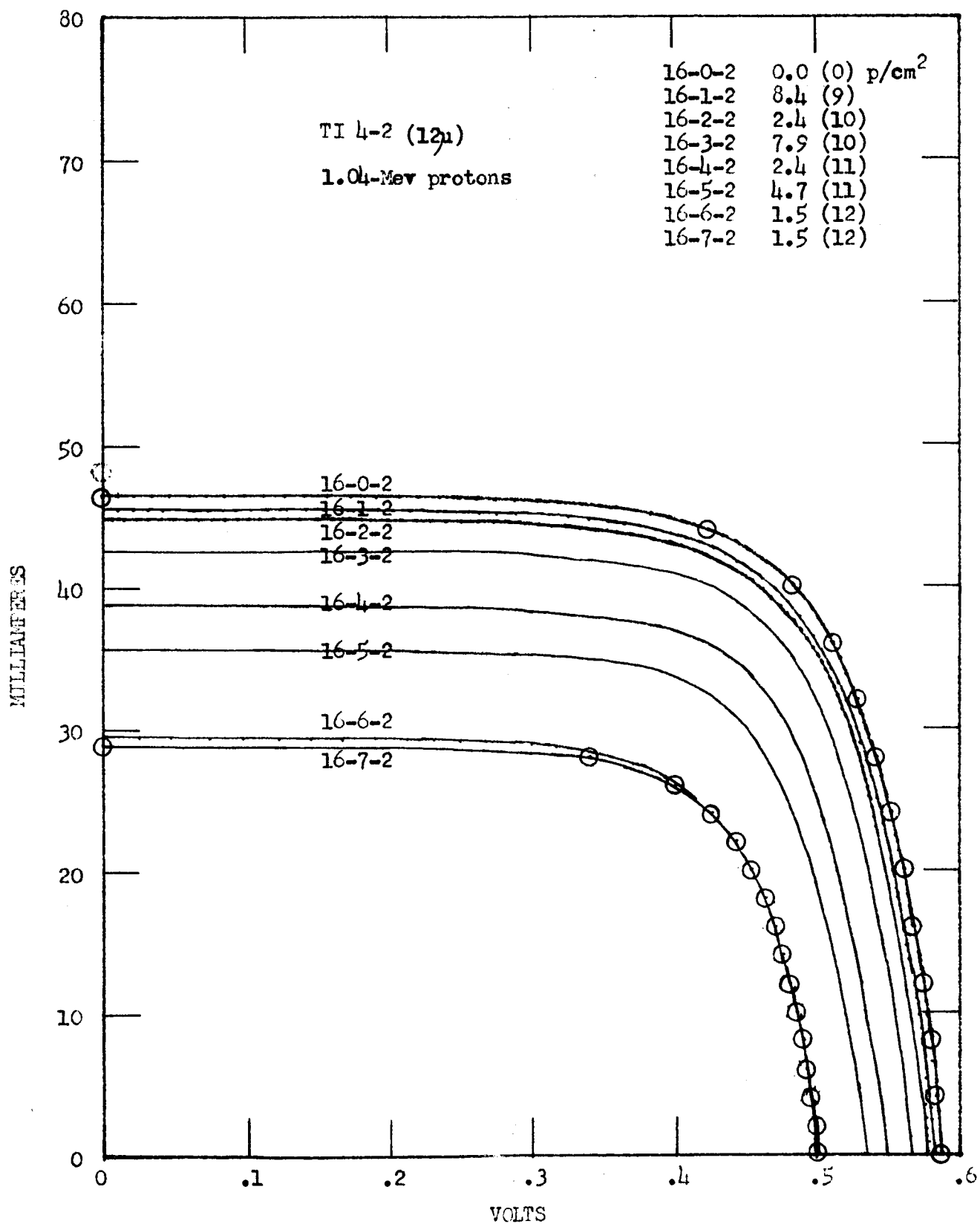


FIGURE 3

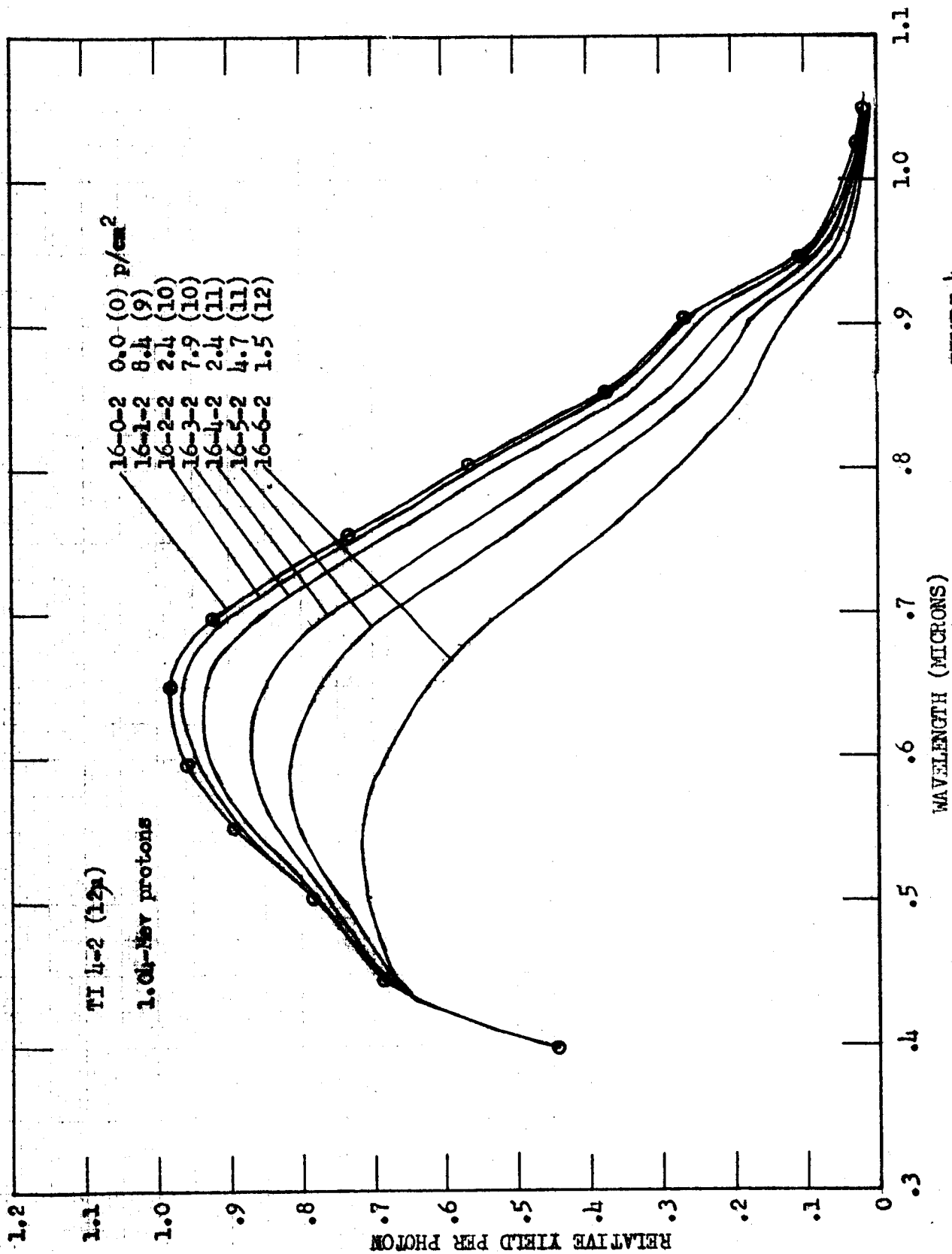


FIGURE 4

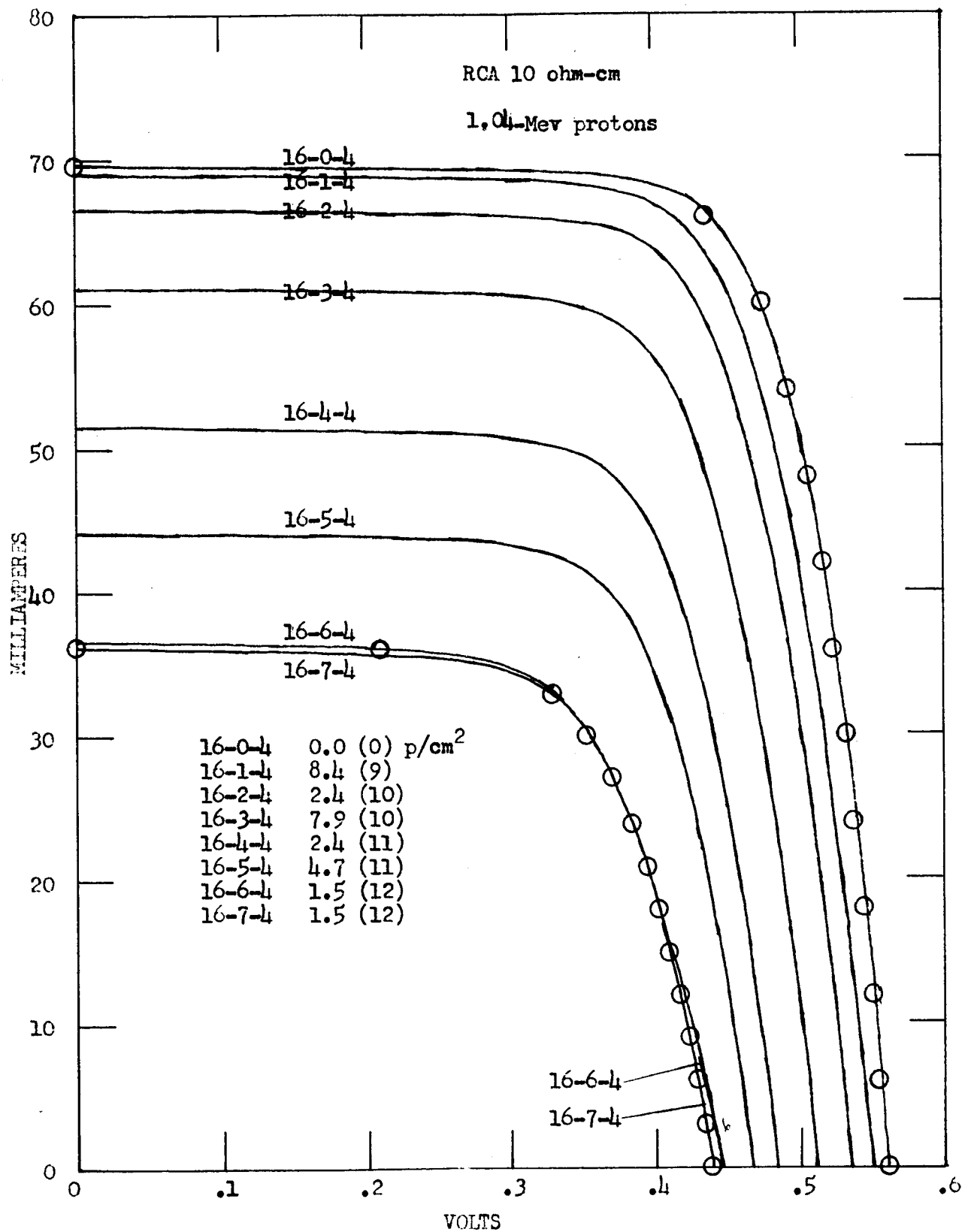


FIGURE 5

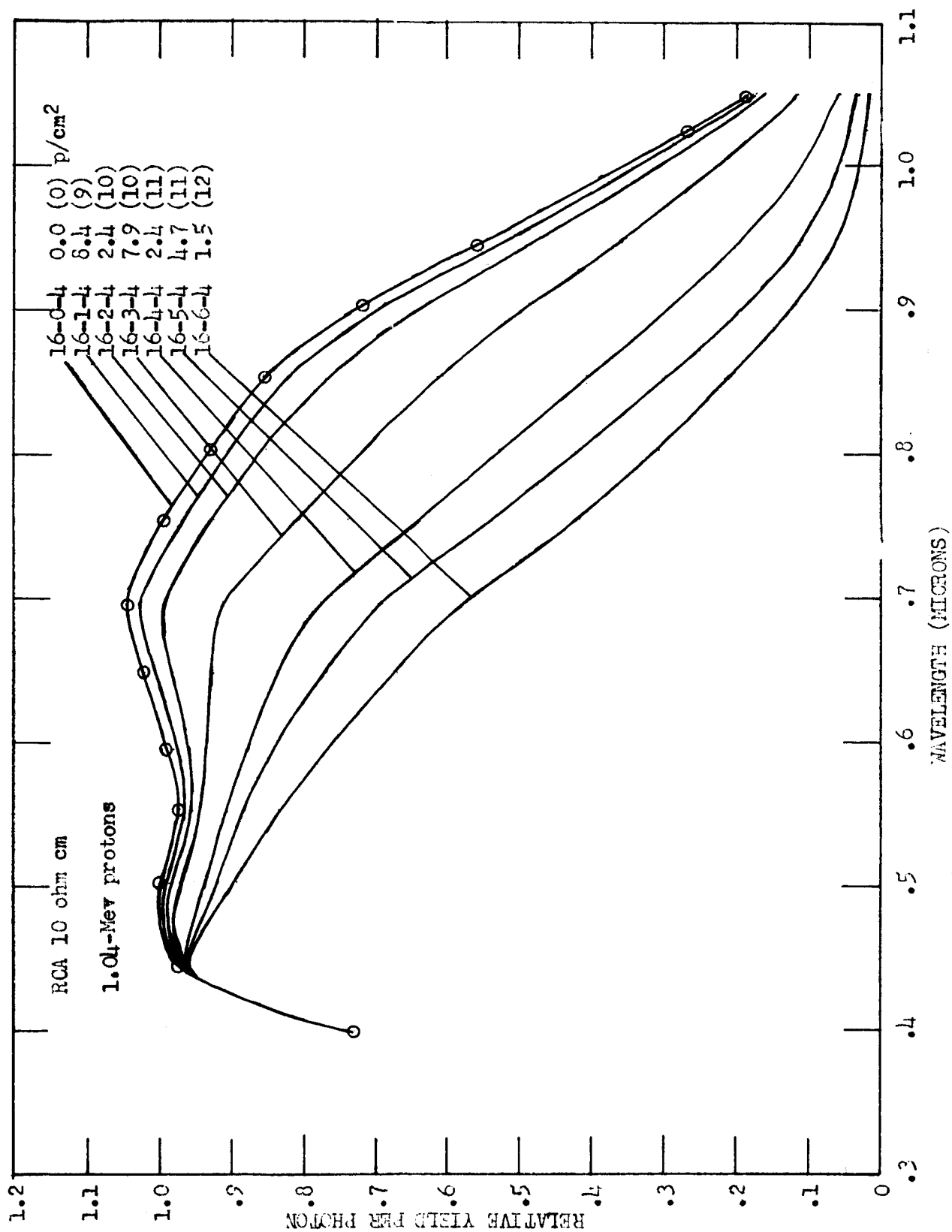


FIGURE 6

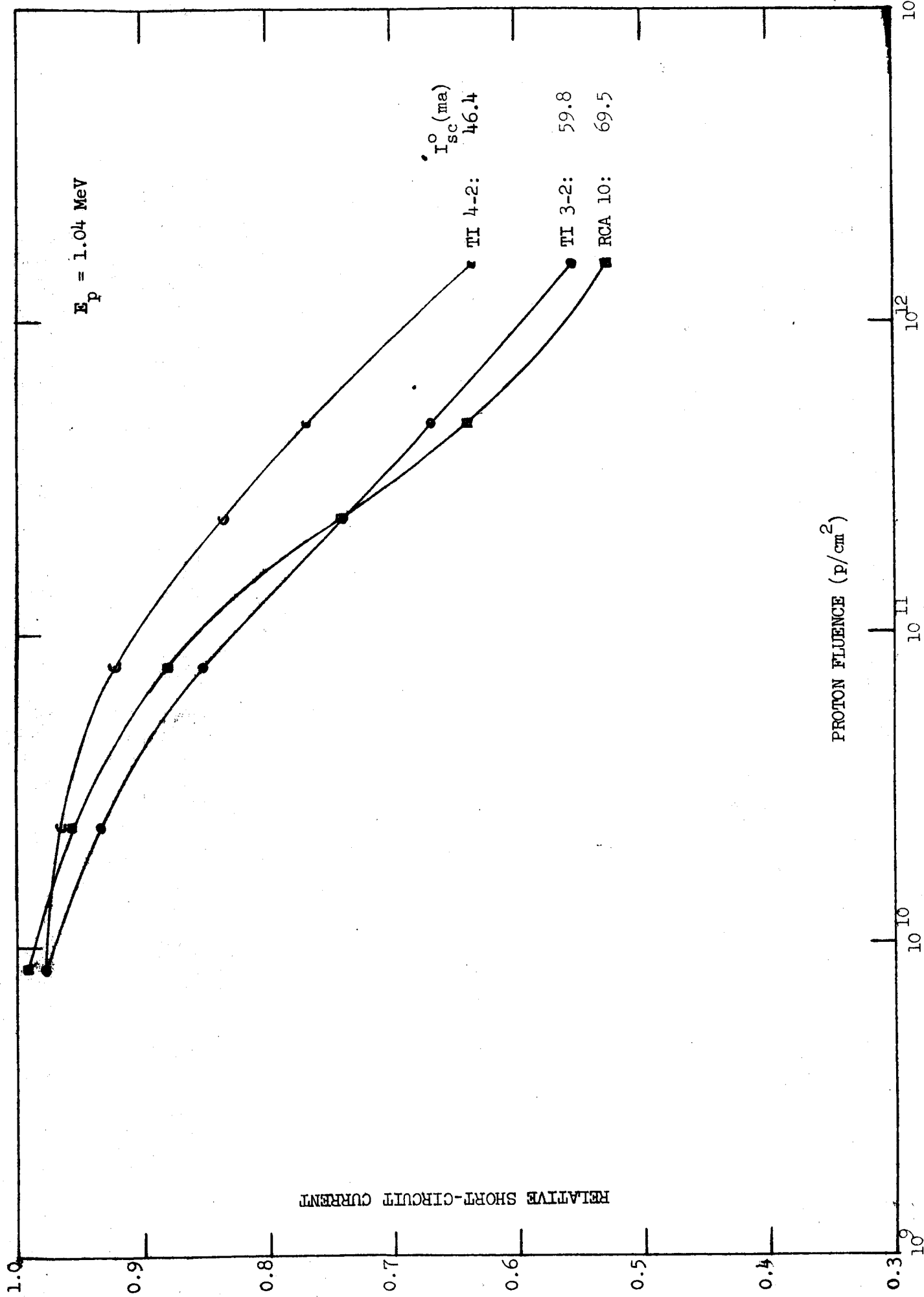


FIG. 7

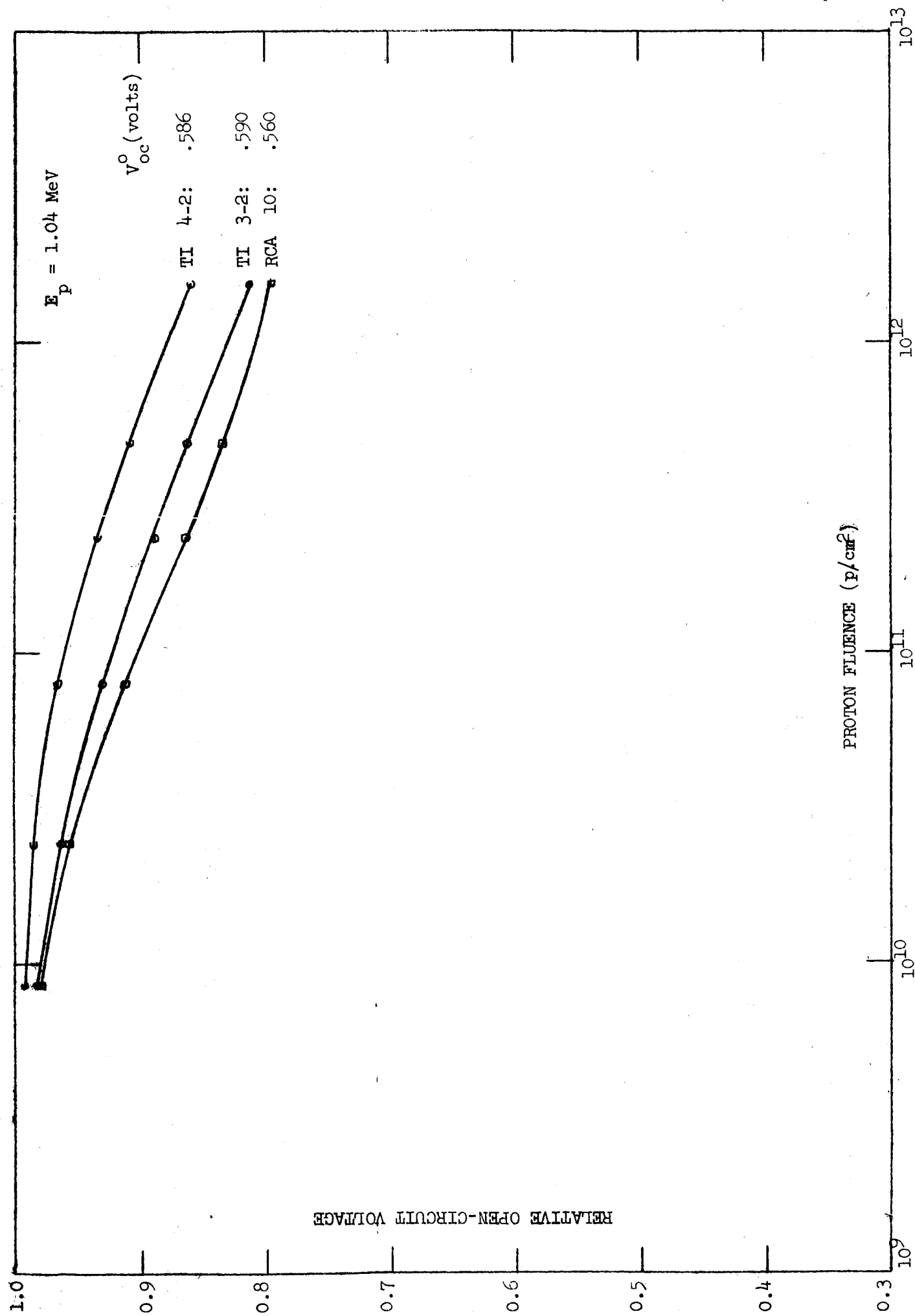
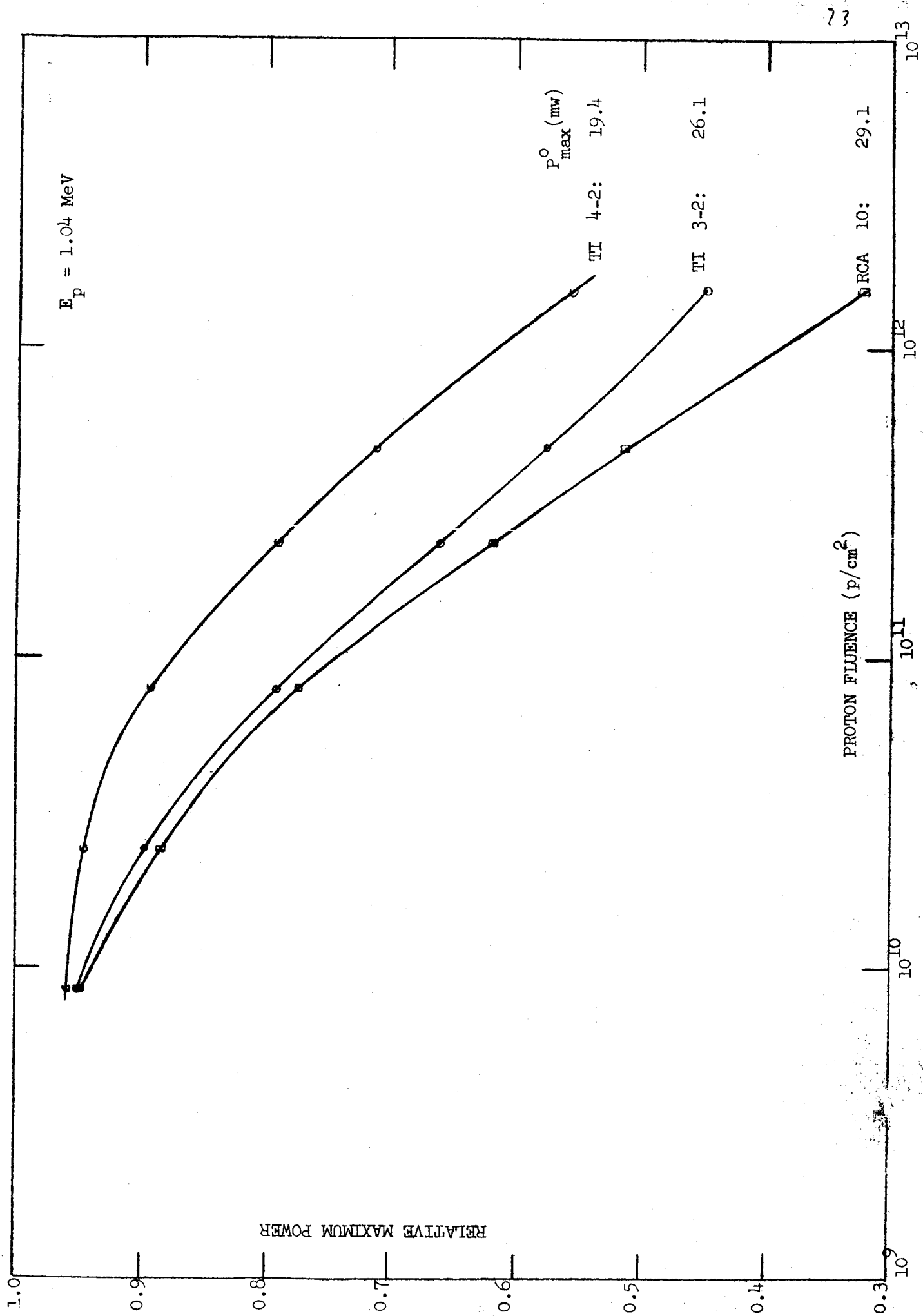


FIG. 8



LIST OF TABLES

- | | |
|---------|---|
| Table 1 | Identification of the Solar Cells |
| Table 2 | Correlation of Proton Fluences and Code Numbers |
| Table 3 | Computer Analysis of I-V data for Solar Cells
Mounted on Disk 16 and Irradiated by 1.04 Mev
Protons |

TABLE 1
IDENTIFICATION OF THE SOLAR CELLS

DISK	POSITION	CELL	BLOCK	PROTON ENERGY
13	1	E-33-1A	N3	2.53Mev
	2	E-33-2C	N4	
	3	H-76	N10 ⁽¹⁾	
	4	H-105	N12	
	5	72	N17	
	6	82	N19	
	7	H-10 Ω cm	19	
	8	H 1 Ω cm	50 ⁽²⁾	
	9	H-110(10 Ω cm)	N22	
15	1	E-34-2D	N5	1.04 Mev
	2	E-35-4A	N6	
	3	H-98	N11	
	4	H-106	N13	
	5	76	N18	
	6	85	N20	
	7	H-10 Ω cm	34	
	8	H-1 Ω cm	37	
	9	RCA 10 Ω cm	N23	
16	1	TI 3-2(25)	N76	1.04 Mev
	2	TI 4-2(12)	N79	
	3	E-54-9b	N82 ⁽¹⁾	
	4	RCA 10 Ω cm	N24	
	5	HOFF 10 Ω cm	A	

TABLE 1 (Cont'd.)
IDENTIFICATION OF THE SOLAR CELLS

DISK	POSITION	CELL	BLOCK	PROTON ENERGY
14	1	H-61	N7	.470 kev
	2	56	N14	
	3	H-10 Ω cm	27	
	4	H-1 Ω cm	33	
	5	TI 3-3 (25)	N77	
	6	TI 4-1 (12)	N78	
	7	E-54-8a	N81	
10	1	E-33-3A	N1	.221 kev
	2	E-33-2A	N2	
	3	H-68	N8	
	4	H-75	N9	
	5	62	N15	
	6	64	N16	
	7	H-1 Ω cm	25	
	8	H-10 Ω cm	45 (3)	
	9	H-109 (10 Ω cm)	N21	
17	1	TI-3-1 (25)	N75	.221 kev
	2	TI 4-3 (12)	N80	
	3	E-55-3b	N83 (1)	
	4	E-55-1c	N84	
	5	HOFF 10 Ω cm	B	
	6	HOFF 10 Ω cm	D	

- (1) This cell was found to have a very low efficiency and was not measured further.
- (2) A small crack initially present in this cell gradually became worse and resulted in a corner breaking off before the irradiation was completed. However, a complete set of I-V curves and spectral response measurements were taken on this cell.
- (3) Corner with lead attached to it broke off sometime after Run 3 was completed.

TABLE 2
CORRELATION OF PROTON FLUENCES* AND CODE NUMBERS

Code** Number	Proton Energy (Mev)	p/cm ²	Code Number	Proton Energy (Mev)	p/cm ²
13-0-X	2.53	0.0 (0)	15-0-X	1.04	0.0 (0)
13-1-X		8.4 (9)	15-1-X		8.2 (9)
13-2-X		2.4 (10)	15-2-X		2.4 (10)
13-3-X		7.9 (10)	15-3-X		8.0 (10)
13-4-X		2.4 (11)	15-4-X		2.4 (11)
13-5-X		4.7 (11)	15-5-X		4.7 (11)
13-6-X		2.0 (12)	15-6-X		1.4 (12)
13-7-X		2.0 (12)	15-7-X		1.4 (12)
16-0-X	1.04	0.0 (0)	14-0-X	.470	0.0 (0)
16-1-X		8.4 (9)	14-1-X		8.0 (9)
16-2-X		2.4 (10)	14-2-X		2.4 (10)
16-3-X		7.9 (10)	14-3-X		9.8 (10)
16-4-X		2.4 (11)	14-4-X		2.4 (11)
16-5-X		4.7 (11)	14-5-X		4.7 (11)
16-6-X		1.5 (12)	14-6-X		1.4 (12)
16-7-X		1.5 (12)	14-7-X		1.4 (12)
10-0-X	.221	0.0 (0)	17-0-X	.221	0.0 (0)
10-1-X		7.8 (9)	17-1-X		7.7 (9)
10-2-X		2.4 (10)	17-2-X		2.4 (10)
10-3-X		7.9 (10)	17-3-X		7.9 (10)
10-4-X		2.4 (11)	17-4-X		2.4 (11)
10-6-X		1.2 (12)	17-6-X		1.2 (12)
10-7-X		1.2 (12)	17-7-X		1.2 (12)

* Number enclosed in parentheses gives exponent of 10.

** Code numbers 10-5-X and 17-5-X were not used because the irradiation was not stopped for measurements on the cells at a proton fluence of 4.7 (11) p/cm² as originally planned.

TABLE 3

COMPUTER ANALYSIS OF I-V DATA OBTAINED FOR SOLAR CELLS MOUNTED ON DISK 16 AND
IRRADIATED BY 1.04-MEV PROTONS

CELL	TEMP	ISC(MA)	VOC(V)	N	RS(OHMS)	PMAX(MW)	IMAX(MA)	VMAX(V)
16-0-1	298.	59.8300	0.5898	2.1875	-0.3987	25.9508	53.8262	0.4821
16-1-1	298.	58.4700	0.5794	2.0892	-0.2442	24.6658	52.6107	0.4688
16-2-1	298.	55.8000	0.5684	1.9857	-0.2104	23.1805	50.3493	0.4604
16-3-1	298.	50.9200	0.5487	1.8695	-0.2393	20.5865	46.0865	0.4467
16-4-1	298.	44.2000	0.5243	1.6604	-0.2513	17.0421	40.1805	0.4241
16-5-1	298.	39.9300	0.5083	1.5351	0.0229	14.9912	36.4327	0.4115
16-6-1	298.	33.2700	0.4789	1.5165	0.0543	11.6110	30.1985	0.3845
16-7-1	298.	32.0500	0.4750	1.5088	-0.0369	11.1643	29.1163	0.3834
16-0-2	298.	46.3700	0.5860	2.3583	-0.4377	19.4131	41.2568	0.4705
16-1-2	298.	45.3000	0.5815	2.3474	-0.3024	18.5728	40.1918	0.4621
16-2-2	298.	44.7200	0.5780	2.3389	-0.3102	18.2211	39.6687	0.4593
16-3-2	298.	42.7300	0.5664	2.1792	-0.2855	17.2563	38.1269	0.4526
16-4-2	298.	38.7500	0.5480	2.0731	-0.2861	15.1888	34.6380	0.4385
16-5-2	298.	35.6500	0.5327	1.8624	-0.1153	13.6774	32.0822	0.4263
16-6-2	298.	29.4000	0.5037	1.8582	-0.2534	10.5997	26.3301	0.4026
16-7-2	298.	28.7500	0.5000	1.8543	-0.5417	10.4636	25.8180	0.4053
16-0-4	298.	69.5200	0.5579	1.3969	0.2181	29.0000	64.2504	0.4514
16-1-4	298.	68.9200	0.5483	1.3085	0.4289	27.6634	63.6666	0.4345
16-2-4	298.	66.4300	0.5355	1.3059	0.4689	25.8004	61.2056	0.4215
16-3-4	298.	61.1700	0.5104	1.3123	0.4534	22.4988	56.1311	0.4008
16-4-4	298.	51.5800	0.4842	1.3917	0.3753	17.8616	46.9548	0.3804
16-5-4	298.	44.3700	0.4670	1.4256	0.3150	14.7847	40.2215	0.3676
16-6-4	298.	36.6400	0.4447	1.6172	0.7344	10.7363	32.2959	0.3324
16-7-4	298.	36.1600	0.4390	1.5748	0.4177	10.8232	32.1403	0.3367
16-0-5	298.	71.5300	0.5442	1.9119	0.0726	27.4585	64.1026	0.4284
16-1-5	298.	71.2000	0.5343	1.7258	0.3221	26.3775	63.9649	0.4124
16-2-5	298.	69.2500	0.5235	1.7837	0.3316	24.7751	61.8072	0.4008
16-3-5	298.	64.9000	0.5000	1.6771	0.4249	21.9728	57.8795	0.3796
16-4-5	298.	56.0000	0.4719	1.5921	0.4479	17.9098	49.9308	0.3587
16-5-5	298.	47.9200	0.4537	1.6695	0.3398	14.6978	42.4387	0.3463
16-6-5	298.	39.7500	0.4250	1.7055	0.4799	11.0344	34.7055	0.3179
16-7-5	298.	38.9800	0.4210	1.7323	0.2020	10.9696	34.1479	0.3212